Design of direct diode pumped amplification stages based on Tm ceramics for kHz rep-rate, kW average power lasers: Design issues and material characterization

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Outline

Context and motivations

- Toward >kW average power ultrashort pulse in Tm, ceramic sesquioxydes hosts

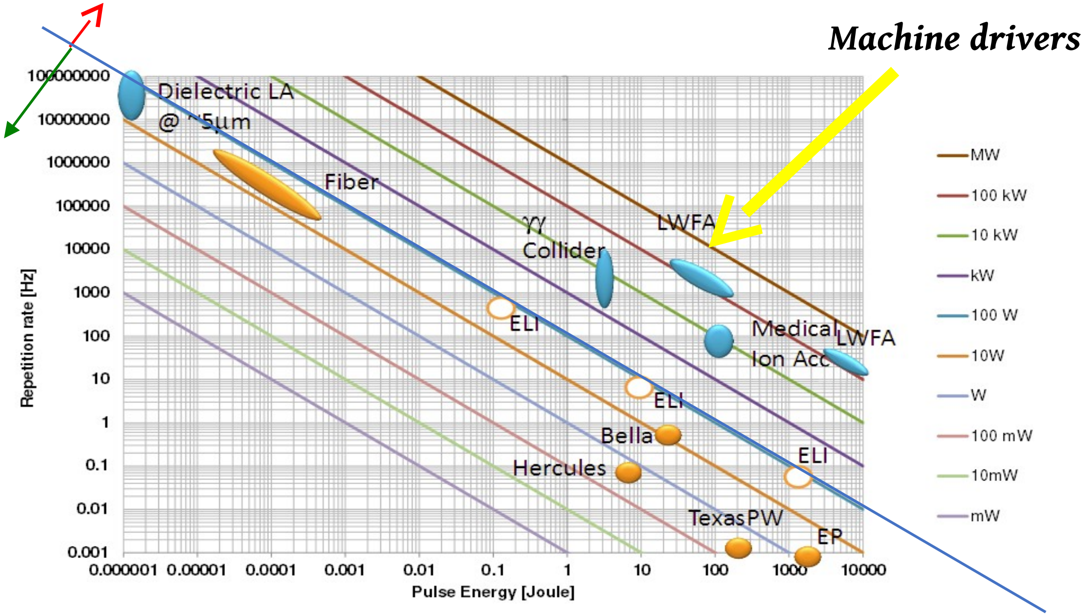
Development of a Tm-based, J-class, 1kHz rep rate amplifier at ILIL

- Design of (side) pumped active mirrors
- Thermal management and cooling architecture
- Ceramic sample optical test; slope efficiency, MPE, cross-relaxation

Summary and conclusions

Context: high average power ultrashort lasers for LWFA

Current reqirement for LPA driver: PW-class system, with high repetition rate (≈kHz)
→ Demanding high average power



The EuPRAXIA laser(s)

Quantity	Baseline Value
Laser 1 - Energy on target	≤ 5–7 J
Laser 1 - Pulse duration	≥ 20–30 fs
Laser 2 - Energy on target	≤ 15–30 J
Laser 2 - Pulse duration	≥ 20–30 fs
Laser 3 - Energy on target	≤ 50–100 J
Laser 3 - Pulse duration	≥ 50–60 fs
Wavelength	800 nm
Repetition rate	20–100 Hz
Energy stability (RMS)	0.6–1 %
Pointing stability (RMS)	~1 µrad

Average power ranging from 1kW to 10kW

Major effort required to fill the gap between existing and required laser technology

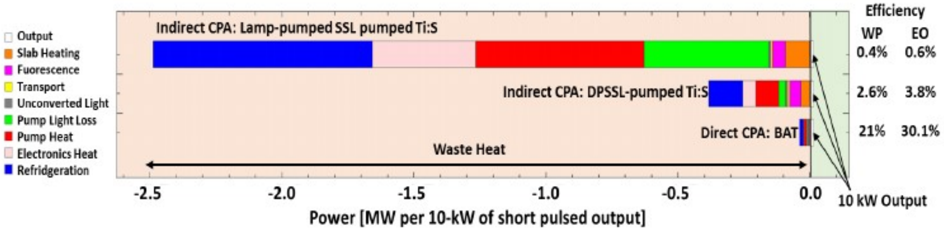
Laser technologies for future accelerators. The Multi-Pulse extraction scheme

Envisioned laser technologies for long term LPA collider modules

- TiSa with incoherently combined pump lasers
- TiSa with diode pumped pump lasers (thick or thin disk)
- Tm:YLF with direct pumping CPA
- Fiber-based lasers with coherent combining

Due to efficiency limitations, TiSa-based technologies unlikely to go beyond the ~kW average power (could be used for injector stage or as single stage LPA for future light sources)

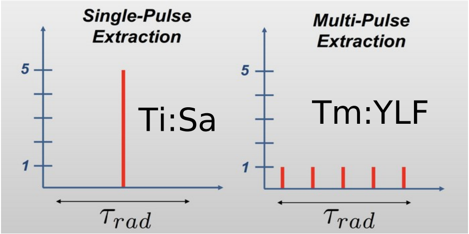
Direct CPA is a solution for high wall-plug efficiency and high rep-rate



C. Siders et al., EAAC 2017

Multi-Pulse Extraction

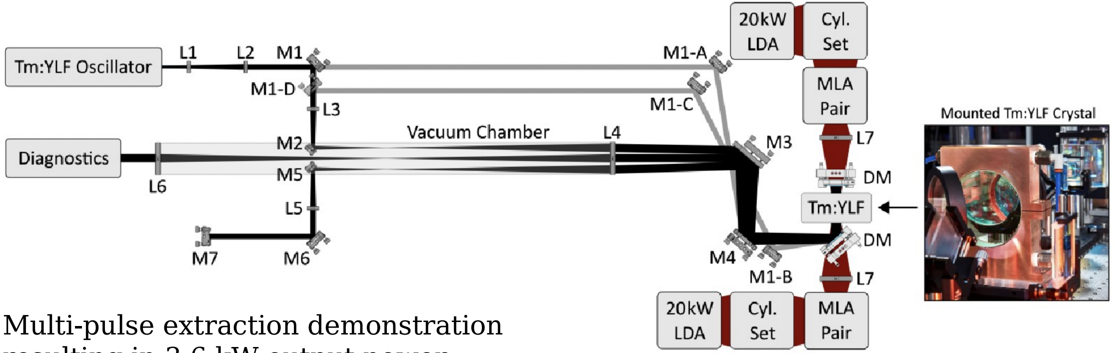
- energy is stored over long (life)times (comparable to the inverse of the rep rate)
- possibility of (quasi)CW pumping, possibly with commercial diodes
- extraction fluence can be much lower than in SPE schemes (possibly affecting the B-integral, …)
- allows the usage of high saturation fluence materials → direct pumping, ...



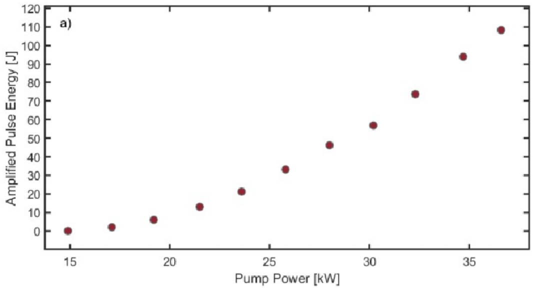
- L.A. Gizzi, F. Mathieu, P. Mason, P P Rajeev, *Laser drivers for Plasma Accelerators*, in Félicie Albert et al, *2020 roadmap on plasma accelerators*, 2021 New J. Phys. 23 031101
- Report on Laser Technologies for kBELLA and beyond (2017)

Recent advances with Tm:YLF

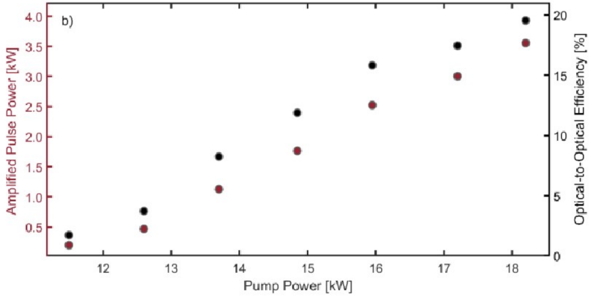
Energy density storage and extraction capabilities of diode pumped Tm:YLF (narrowband)



Amplified pulse energy measurements up to **108.3 J** for the 6-pass Tm:YLF power amplifier



Multi-pulse extraction demonstration resulting in 3.6 kW output power



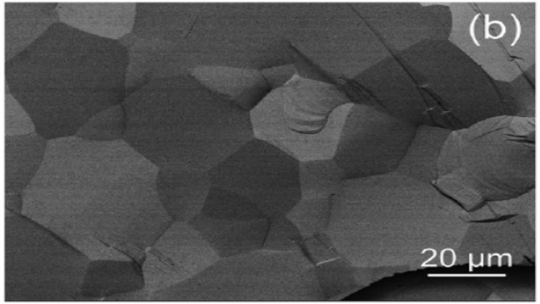
- “The multiple proof-of-principle demonstrations [..] reveal the potential for high efficiency, high energy density extraction using Tm:YLF for future high peak and average power laser systems.”
- “Additional efforts are currently in progress to conduct chirped pulse amplification of ultrashort pulses using Tm:YLF at the joule-level for the first time.”

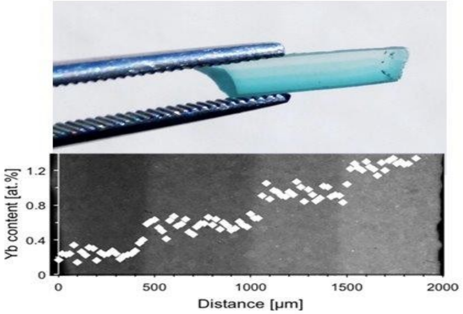
Issa Tamer, et al., "High energy operation of a diode-pumped Tm:YLF laser," Proc. SPIE 12401

Laser grade ceramic option

- Faster and cheaper vs. single crystal growth process – for cubic crystalline structure.
- Large components, -shaping, -graded doping also optimized for thermal management – **features not available for single crystals.**
- Several compositions (e.g. **YAG, LuAG , Sc_2O_3, Lu_2O_3**) and dopants (**Nd, Yb, Er, Tm**…) already available
- Spectroscopic and thermomechanical properties similar to those of the corresponding single crystals
- Better uniformity of dopant distribution on large gain elements

Industrial and R&D effort: KONOSHIMA (Japan); Research in China, Japan, Russia, USA, France and Italy (ISTEC-CNR) (ZENIT Smart Polycrystals)





Ceramic option: Tm in sesquioxide hosts

Sesquioxides doped with Tm3+, such as Tm:Lu2O3, Tm:Y2O3, and Tm:Sc2O3, are also emerging materials: their better thermo-optical properties make them promising for power scaling applications.

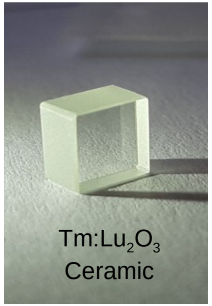
The growth of sesquioxide single crystals is very complicated, while it is possible to produce them in transparent ceramic form thanks to their cubic crystalline structure and optical isotropy.

Advantages of ceramic medium:
High thermal and mechanical features
Scalable size
Custom doping
Optimize energy efficiency

→

Best "hosts" for Thulium:

- **yttrium lithium fluoride (YLF),**
- **yttrium aluminum garnet (YAG)**
- **Lutetium oxide (Lu_2O_3)**



Sample from Konoshima

C. Krankel, IEEE J. Sel. Topics Quantum Electro 21, Art. no. 1602013 (2015)

Sesquioxydes thermal conductivity

Thermal conductivity in W/m/K of different sesquioxide crystals in comparison to YAG with and without Yb-doping. Values in [] are estimated.

Temperature	30°C	50°C	60°C	70°C	80°C	90°C	100°C
Sc_2O_3	[16.5]	15.5	14.9	14.4	13.9	13.6	13.3
Yb(2.8%):Sc_2O_3	6.6	6.4	-	6.5	-	-	6.3
Y_2O_3	[13.6]	12.8	12.4	12.0	11.6	11.2	10.8
Yb(2.7%):Y_2O_3	7.7	7.4	-	7.2	-	-	6.8
Lu_2O_3	[12.5]	12.2	11.9	11.6	11.2	10.8	10.3
Yb(2.7%):Lu_2O_3	11.0	10.8	10.7	10.6	10.3	10.1	9.8
YAG	11	-	-	9.2	-	-	8.4
Yb(5%):YAG	6.8	-	-	6.3	-	-	6.0

The thermal conductivity depends on the host and decrease by increasing the doping concentration. **Undoped sesquioxides show the highest values.** Moreover, in matrices contening Lu3+ it is not affected by doping levels.

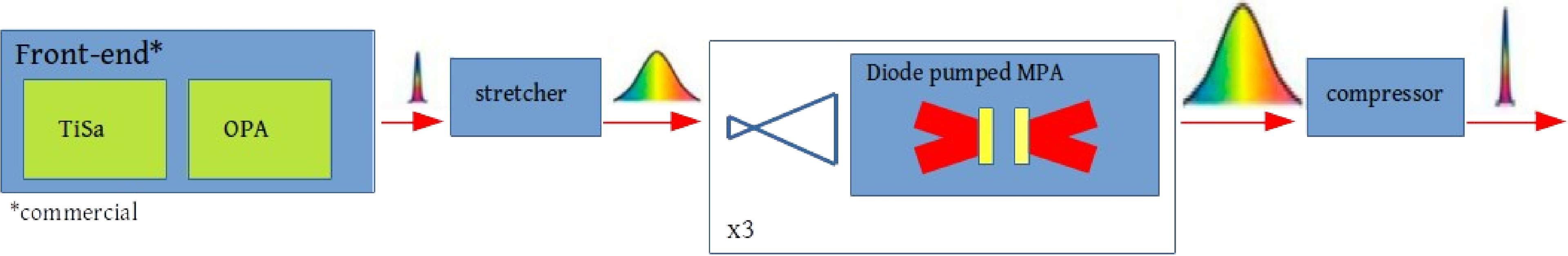
R. Peters et al., *Appl Phys B Lasers Opt*. 102(3), 509, (2011;
U. Griebner et al.,Opt. Express 12(14), 3125 (2004)

A. Pirri et al., Materials 15, 2084 (2022)

Selected material for 1J-1kHz power amp at ILIL: ***Tm:Lu2O3***

- Emission at 2 μm (eye-safe)
- Large amplification bandwidth
- Direct pumping at 800 nm, using diodes operating in (quasi) CW mode (available and scalable)
- Multi-pulse extraction at high repetition rate > 1 kHz; Ideal for accelerator technology
- Mature ceramic production technology

Khz laser development at ILIL-INO-CNR



3 amplification stages, each based on a 2 active media multipass scheme. Active mirror config, with cooling carried out on the rear side on both sides

Selected doping: 4% at

Pulse energy (goals/expected):
>1mJ seeding the 1st amp
~8 mJ seeding 2nd amp
>50mJ seeding the 3rd amp
>500mJ from 3rd amp

Amplifier concept: active mirror with edge pumping and face cooling

Wide-Bandwidth Tm-Based Amplifier for Laser Acceleration Driver[a]

Drew A. Copeland[b], John Vetrovec , and Amardeep S. Litt
Aqwest LLC
Larkspur, CO USA

High Energy/Average Power Lasers and Intense Beam Applications VIII, edited by Steven J. Davis, Michael C. Heaven, J. Thomas Schriempf, Proc. of SPIE Vol. 9729, 97290I · © 2015 SPIE · CCC code: 0277-786X/15/$18 · doi: 10.1117/12.2220010

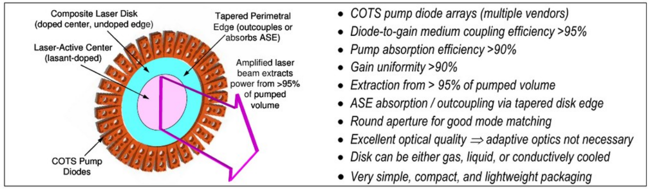
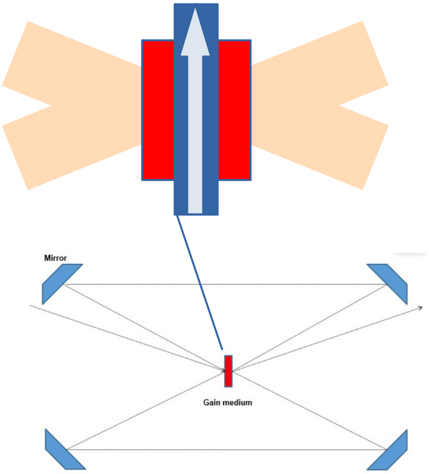


Figure 11. *Edge-pumped disk laser module uses standard commercial off-the-shelf (COTS) diodes closely coupled to the disk edge for high efficiency, uniform gain, and compact packaging.*

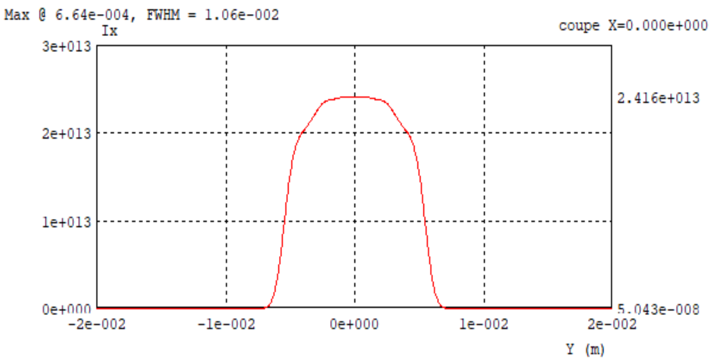
Liquid cooling

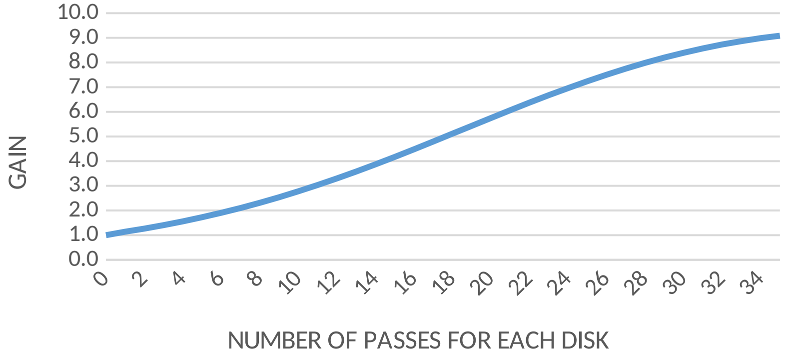


Optical simulation of extraction from 3rd amplifier

	SEED DIAMETER (mm)	SEED PROFILE	PUMP DIAMETER (mm)	PUMP PROFILE	PUMP ENERGY DENSITY (J/m3)	TOTAL PUMP ENERGY (mJ)	INPUT ENERGY (mJ)	OUTPUT ENERGY (mJ)	NUMBER OF PASSES FOR EACH DISK	PEAK OF INTENSITY (W/m2)	PEAK OF FLUENCE (J/cm2)	EXTRACTION EFFICIENCY
STANDARD	8.5	SUPERGAUSSIAN OF ORDER 2	16	SUPERGAUSSIAN OF ORDER 5	3.00E+06	3600	56	508	35	2.4E+13	0.6	0.14
+5% PUMP ENERGY	8.5	SUPERGAUSSIAN OF ORDER 2	16	SUPERGAUSSIAN OF ORDER 5	3.2E+06	3780	56	563	35	2.58E+13	0.64	0.15
-5% PUMP ENERGY	8.5	SUPERGAUSSIAN OF ORDER 2	16	SUPERGAUSSIAN OF ORDER 5	2.90E+06	3420	56	456	35	2.2E+13	0.55	0,13

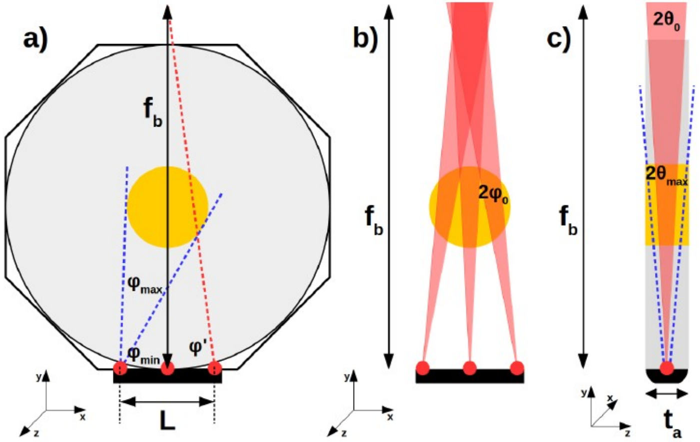
OUTPUT BEAM STANDARD CONFIGURATION





Pumping ray-tracing: the general scheme

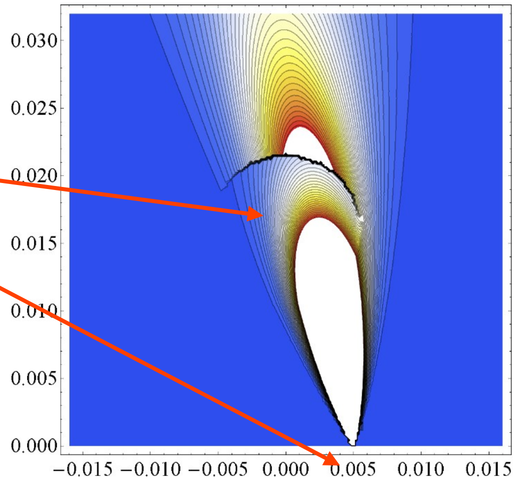
Ray-tracing code developed to model the pump absorption
Allows the pumping configuration (diode bars #/geometry, diode bars focusing/divergence, pump beam longitudinal reflection on surfaces, ...) to be optimized (in terms of overall pump energy absorption, transverse/longitudinal homogeneity, ...)
Doping longitudinal/transverse tailoring allowed



If the irradiation occurs through **optical fibers**, the model still holds (divergence angles depends on the numerical aperture).

D. Palla *et al*,, Opt. Laser Techn. 156, 108524 (2022)

Single Bar (3 subarray, directed at center)



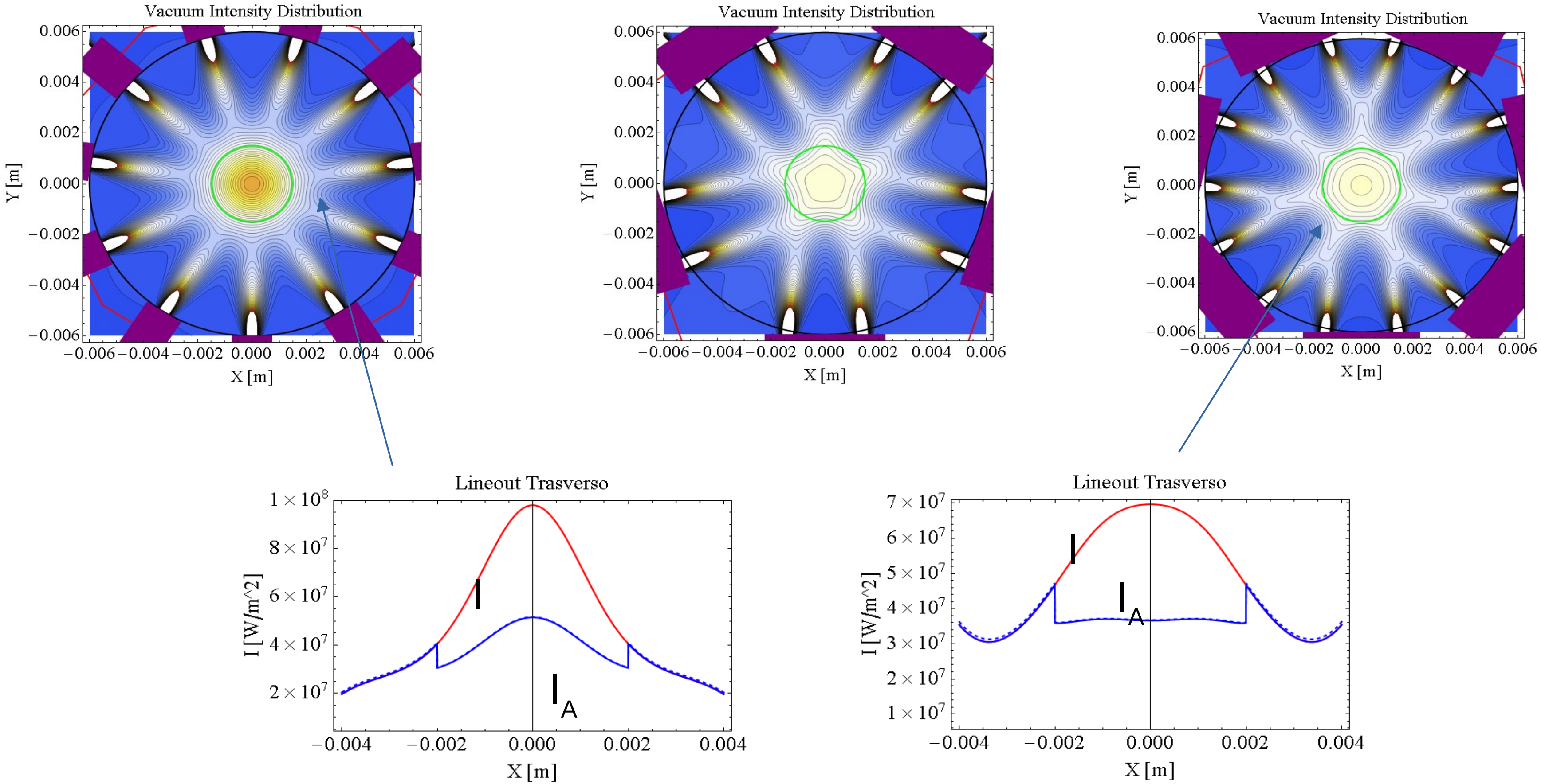
$$I(\mathbf{x}, x_s) = \frac{P_s}{\pi y^2 \varphi_0 \theta_0} \exp\left(-\left[\left(\frac{x - f(y)x_s}{y\varphi_0}\right)^2 + \left(\frac{z}{y\theta_0}\right)^2\right]\right)$$

$$I^{(abs)}_{b,s}(\mathbf{x}, \mathbf{x}_b, \beta_b, x_s) \simeq I_{b,s}(\mathbf{x}, \mathbf{x}_b, \beta_b, x_s)\, T_{b,s}(\mathbf{x}, \mathbf{x}_b, \beta_b, x_s)$$

$$T_{b,s}(\mathbf{x}, \mathbf{x}_b, \beta_b, x_s) = \exp\left(-\int_{\mathbf{x}^*}^{\mathbf{x}} \alpha(\mathbf{x}')\hat{\mathbf{e}}_r(\mathbf{x}') \cdot d\mathbf{x}'\right)$$

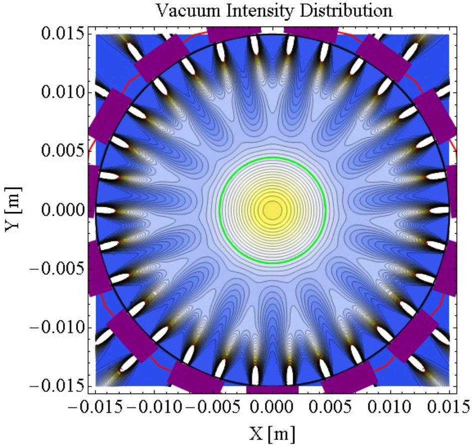
$$Q_b(\mathbf{x}, \mathbf{x}_b, \beta_b) = \alpha(\mathbf{x}) \sum_{s=0}^{N_s-1} I_{b,s}(\mathbf{x}, \mathbf{x}_b, \beta_b, x_s)\, T_{b,s}(\mathbf{x}, \mathbf{x}_b, \beta_b, x_s).$$

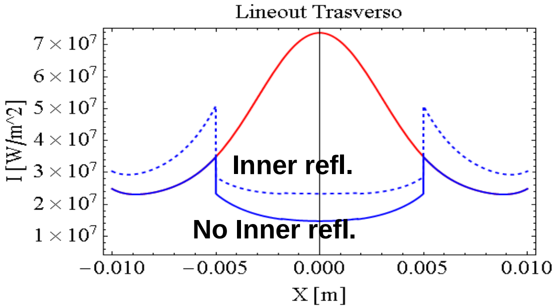
Sample results (1st amp) for different "focusing" configurations

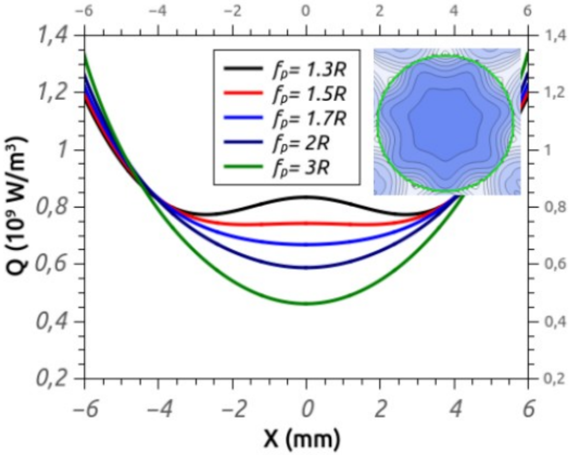


D. Palla *et al*,, Opt. Laser Techn. 156, 108524 (2022)

Sample results for 3rd amp







	Radial	Focus A	Focus B	Focus C
Sides	11	5	7	15
Diode Power (W)	40	45	35	70
Total diodes power (W)	440	450	490	2100
Focus (mm)	∞	15	15	80
Numerical aperture	0.17	0.17	0.17	0.17
% Power (doping radius)	57.6	58.5	58.2	82.8
% Power (extraction radius)	47.6	34.3	34.1	67.5
Optical Power (J/ms)	0.14	0.1	0.11	0.92

D. Palla *et al*, Opt. Laser Techn. 156, 108524 (2022)

Thermal management: numerical modelling

Preliminary modelling of thermal management carried out using a custom code to look for an initial working point, using “reasonable” heat transfer coefficients

Detailed 3D maps of pump energy density obtained from optical simulations

Order of magnitude of power density

$$\langle Q \rangle \simeq \frac{E_P \eta_h \nu_r e p}{\pi r^2 d} \sim 2 \times 10^9 \, \mathrm{W/m^3}$$

Material: Tm^{3+}:Lu_2O_3
Doping level: 4%
Geometry: Thin disk configuration (the doped active region is represented in yellow in the figure)
Thickness: d=3 mm

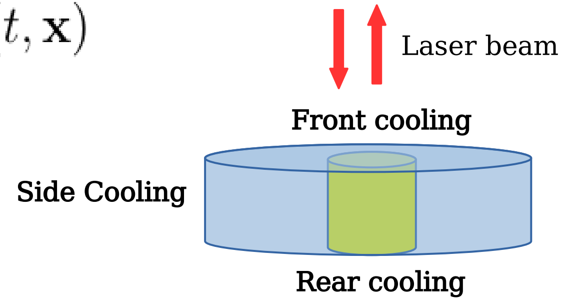
Heat Trasfer Equation

FEM numerical solution (using Mathematica)

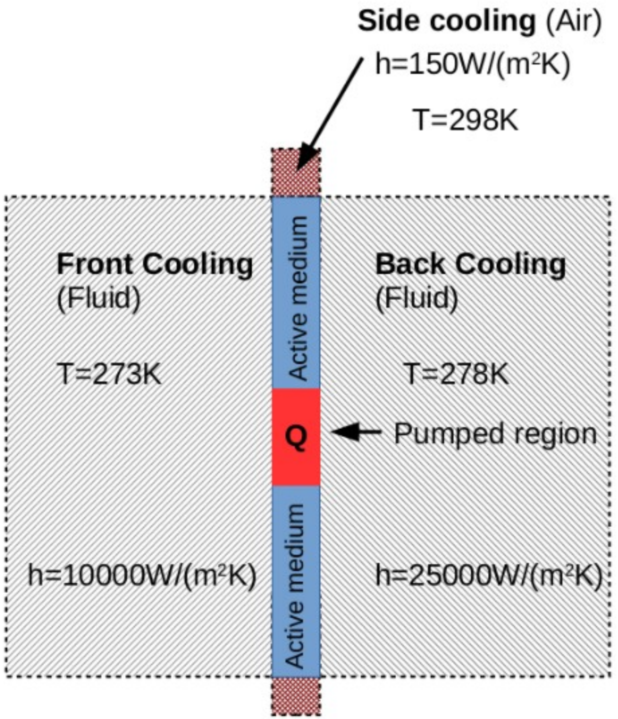
$$\rho\, C_P\, \partial_t T(t,\mathbf{x}) + \nabla \cdot \left[-k\, T(t,\mathbf{x})\, \nabla T(t,\mathbf{x})\right] = Q(t,\mathbf{x})$$

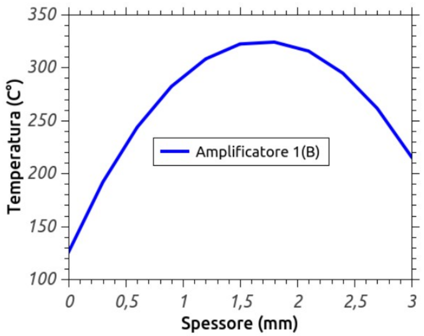
Neumann contition on spatial boundaries

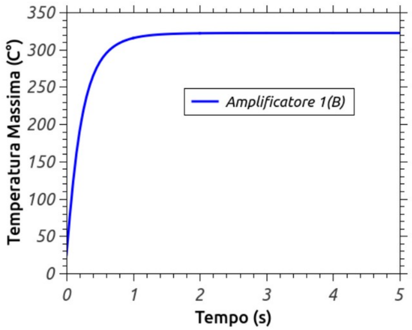
$$\frac{\partial T}{\partial n} = \frac{h}{k}\left[T_{\text{ext}}(t,\mathbf{x}) - T(t,\mathbf{x})\right]$$

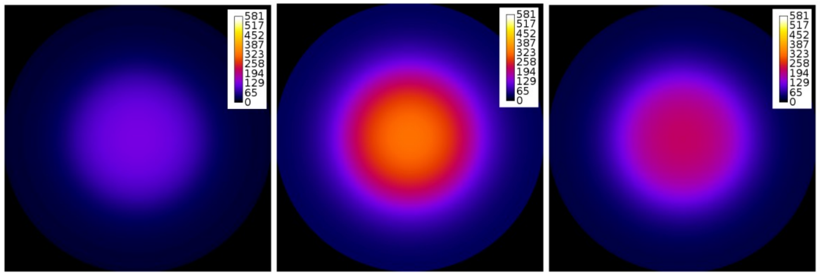


The general cooling scheme

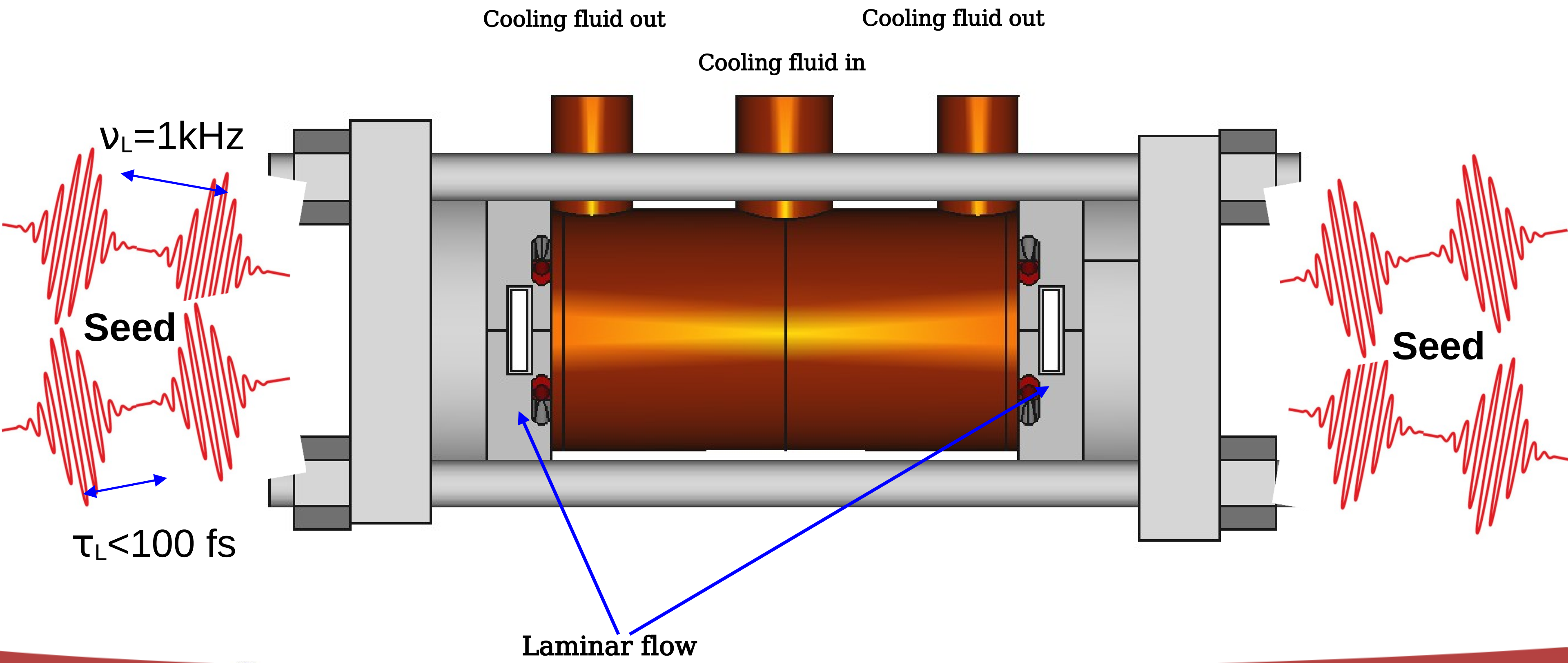




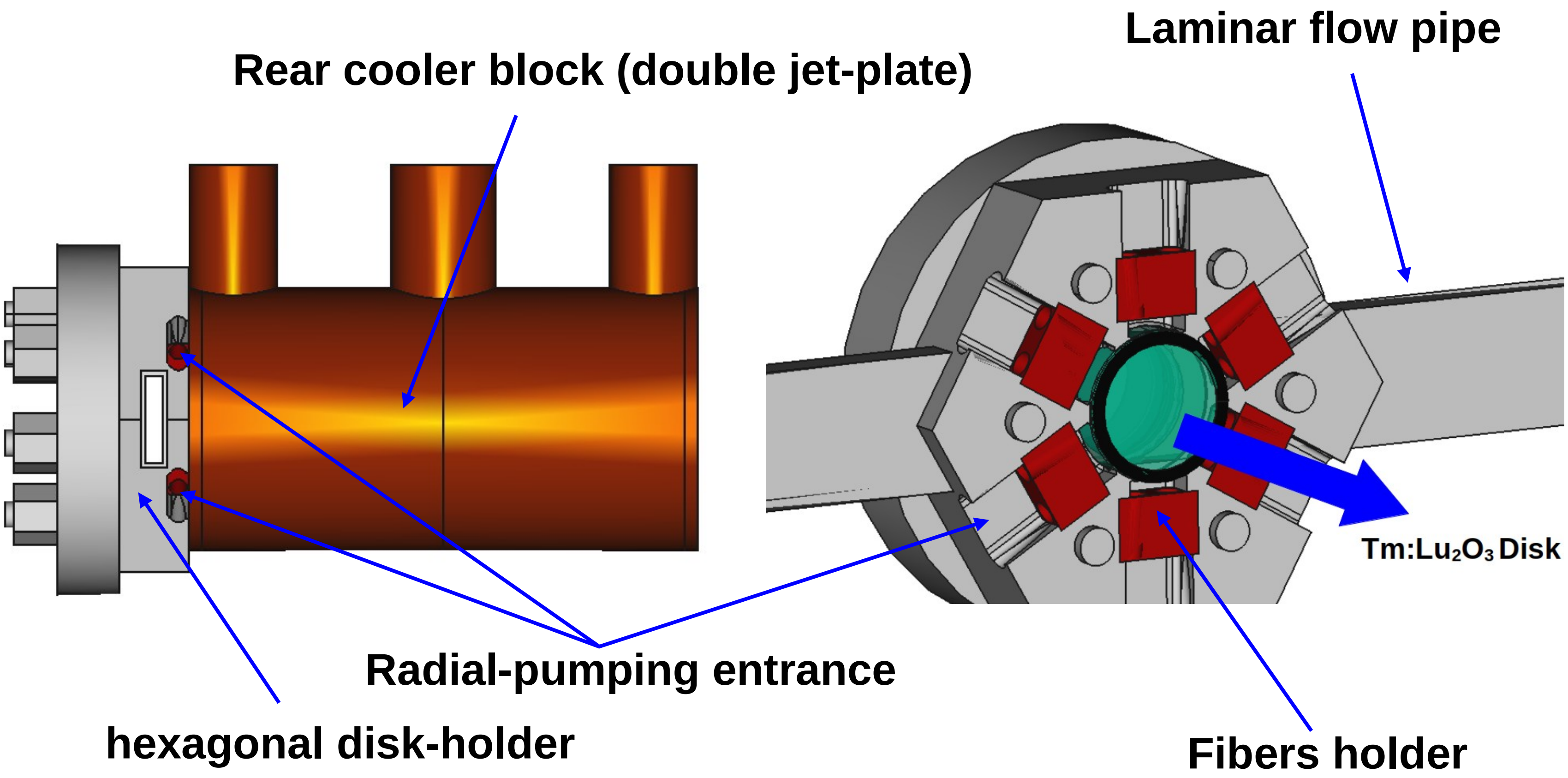




Mechanical design of (2) active medium holder

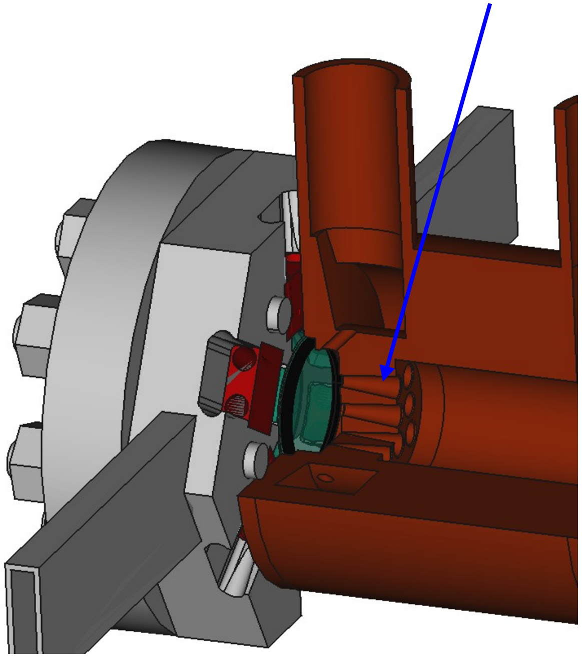


Mechanical design of (2) active medium holder

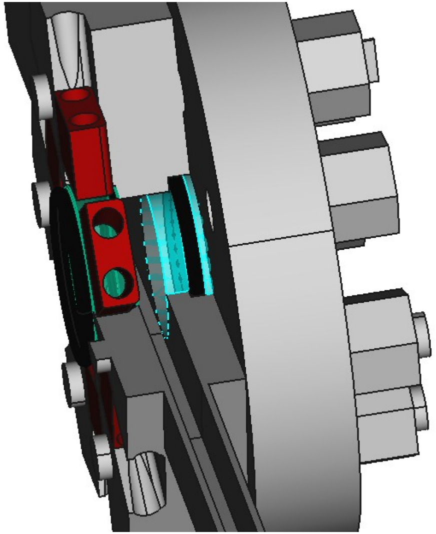


Mechanical design of (2) active medium holder

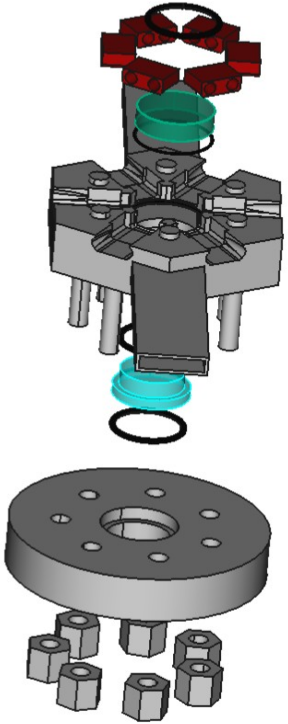
Jet-plate



Laminar cooling detail



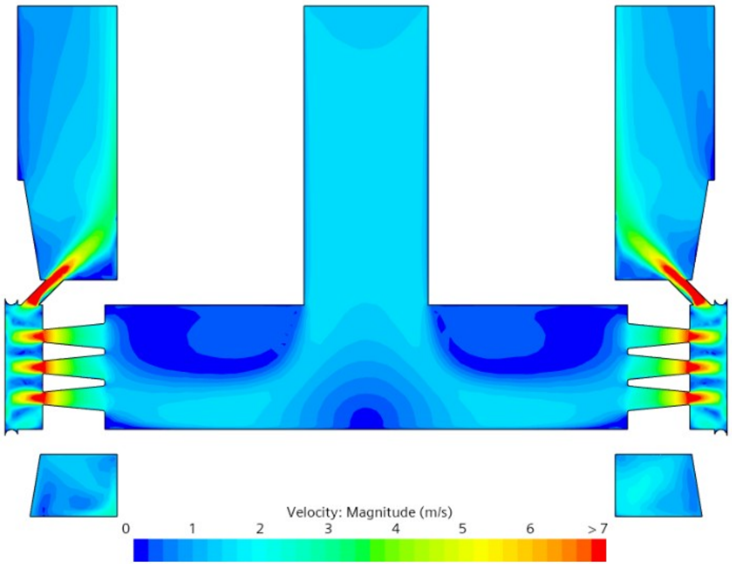
Exploded-view



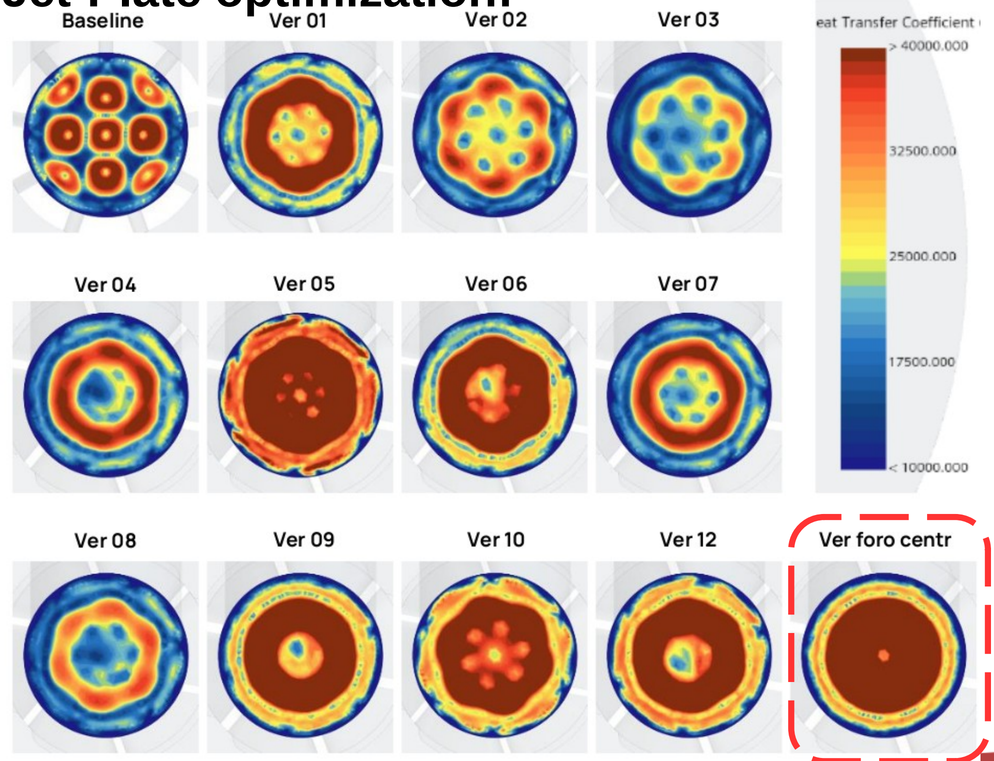
Jet-Plate Simulations (target h>25000 W/(m^{2}k))

Fluid tubes and jets design optimized using fluid dynamics/heat transfer dynamics simulations, aiming at reaching a value of *h>25000 W/(m2 K)*

Baseline design:



Jet-Plate optimization:



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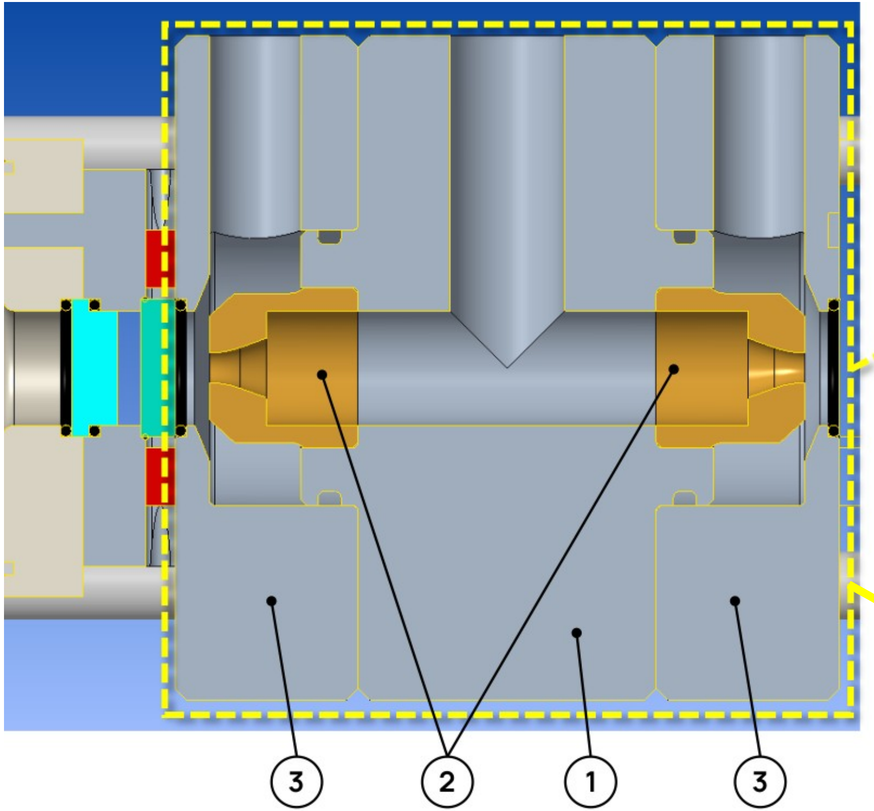
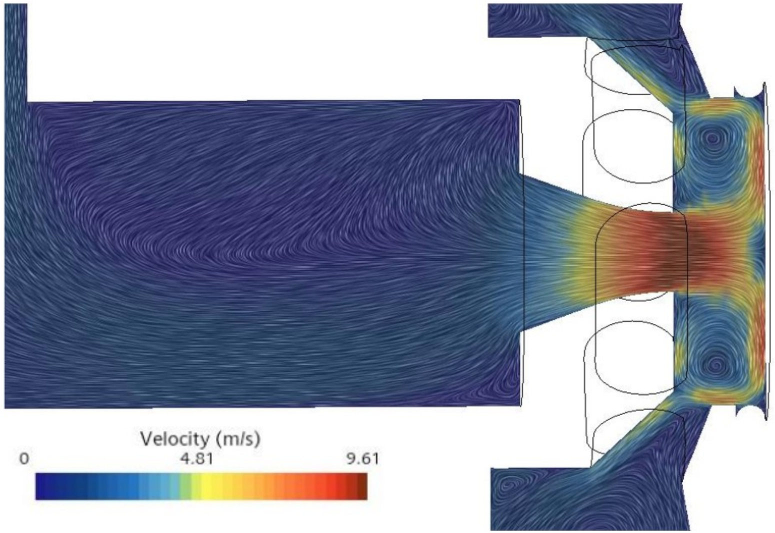
Final design of rear side cooling circuit



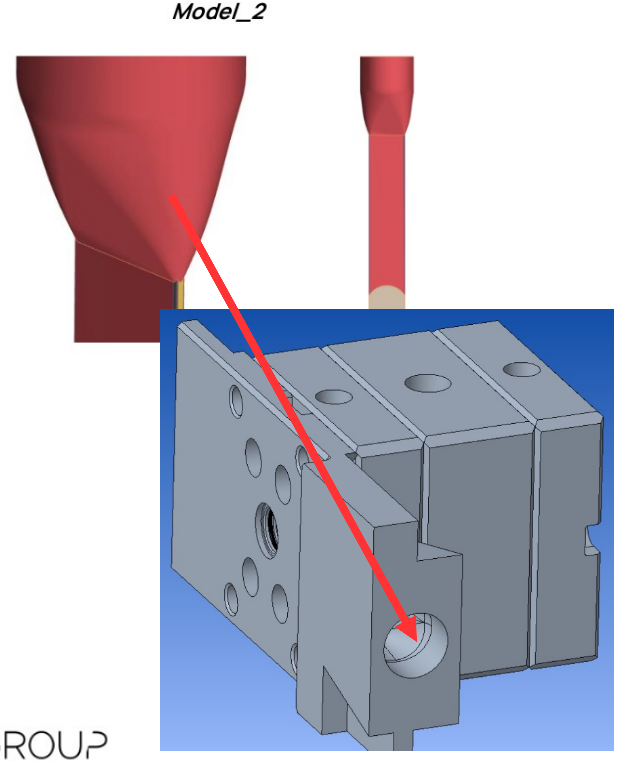


Central cooler final design
(2.6 mm diameter single nozzle)

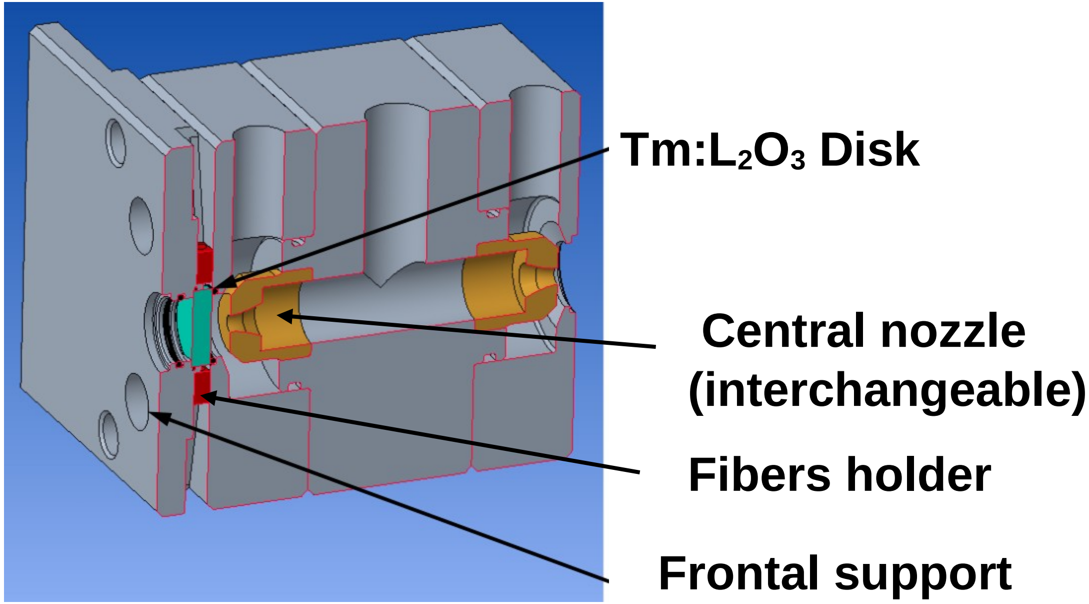
1)Central part (circuit inlet)
2)Axial flux inlet
3)Site part (circuit outlet)

Front side cooling

Aim: reaching a value of *h>10000 W/(m2 K),* with a laminar flow

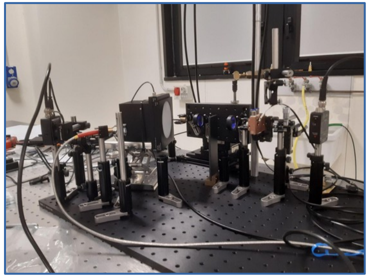


Full assembled support

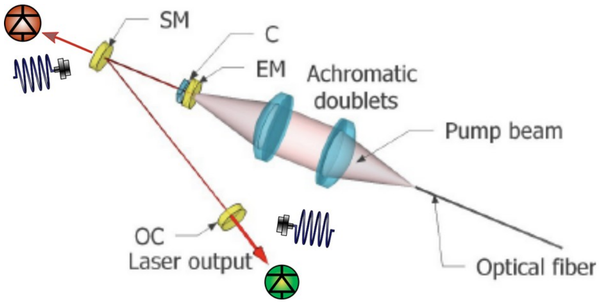


Optical characterization of a Tm:Lu2O3 ceramics

Test bench built at ILIL, to characterize a test sample from Konoshima



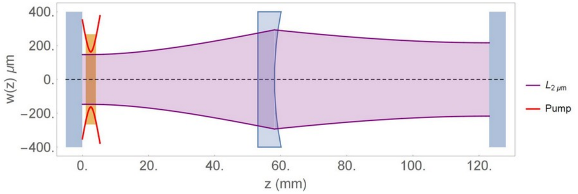
C: Ceramic active medium
EM: End mirror (R > 99.9%)
SM: Spherical mirror (R > 99.9%)
OC: Output coupler (R = 85,90,97%)
f2f Telescope (f = 5cm)



Diode pump (from Alite, Italy)
- Tunable laser diode
- λ = 790 – 800 nm
- CW to 1 kHz frequency
- Power 10 – 70 W

Output optical fiber
- Φ = 200 μm
- N.A. = 0.22

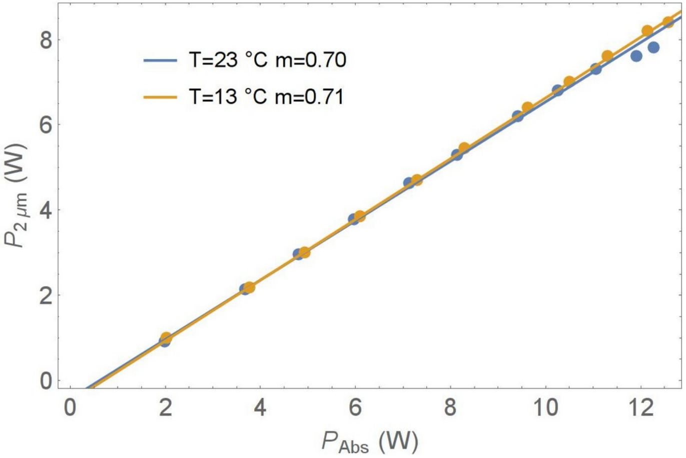
Pump beam
- 160 × 160 μm beam
- $M^2 \approx 150$



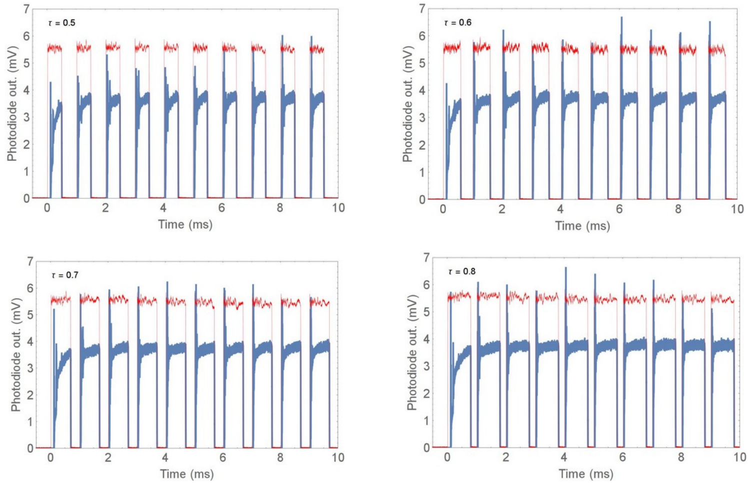
Cavity geometry
- Longitudinal pumping
- Beam waist depends on OC position
- 140 μm beam waist for 65 mm OC distance

Slope efficiency and hint of cross-relaxation

Retrieved slope efficiency ~70%
W/r to similar results (although obtained with different conditions, hosts, ...), points at a contribution of the so-called "cross-relaxation" process



Time-behaviour: Multi-Pulse Extraction



Laser emission growing over pulses (rep-rate 1kHz), as expected due to the upper state lifetime spanning multiple pulses

Multi-pulse extraction dynamics: rate equations (atomic) modelling

The role of the extraction by multiple pulses (made possible by the ~3.8ms lifetime) is being investigated using atomic physics modelling based on the rate equations

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Highly Efficient, Compact Tm^{3+}:RE_2O_3 (RE = Y, Lu, Sc) Sesquioxide Lasers Based on Thermal Guiding

Pavel Loiko, Philipp Koopmann, Xavier Mateos, Josep Maria Serres, Venkatesan Jambunathan, Antonio Lucianetti, Tomas Mocek, Magdalena Aguiló, Francesc Díaz, Uwe Griebner, Valentin Petrov, and Christian Kränkel

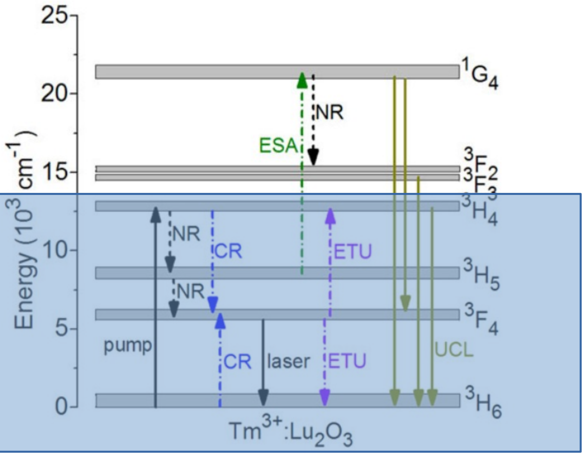
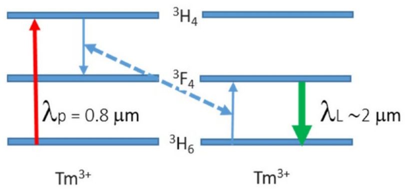


Fig. 1. Scheme of energy levels of the Tm^{3+} ion (on the example of Tm^{3+}:Lu_2O_3, C_2 site) showing relevant processes (CR: cross-relaxation, ETU: energy-transfer upconversion, ESA: excited-state absorption, UCL: upconversion luminescence, NR: non-radiative relaxation). The grey rectangles correspond to the total Stark splitting [30].

$$\frac{dn_i}{dt} = A_{ij}(t)\, n_j + B_{ijk}(t)\, n_j\, n_k$$

"Cross-relaxation" process

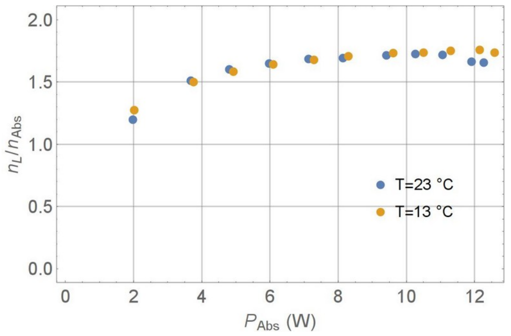


"two-for-one cross-relaxation mechanism"

Figure 2. Scheme of the cross-relaxation (CR) process.

overall quantum efficiency approaches 2 (beyond Stokes limit)

Experimental results points at a CR factor >1.5 in our case



Multi-pulse extraction dynamics: rate equations (atomic) modelling results

Rate equations (with transition rates based upon available data ...) + "forced" extraction

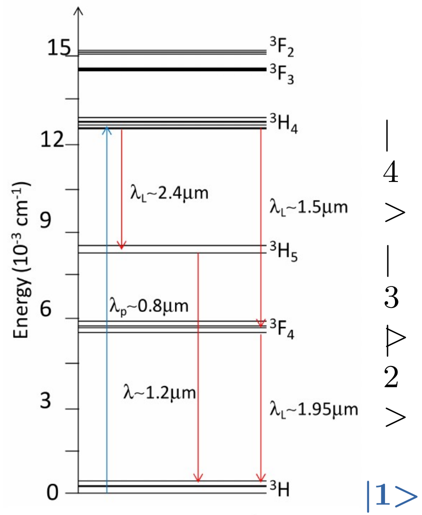
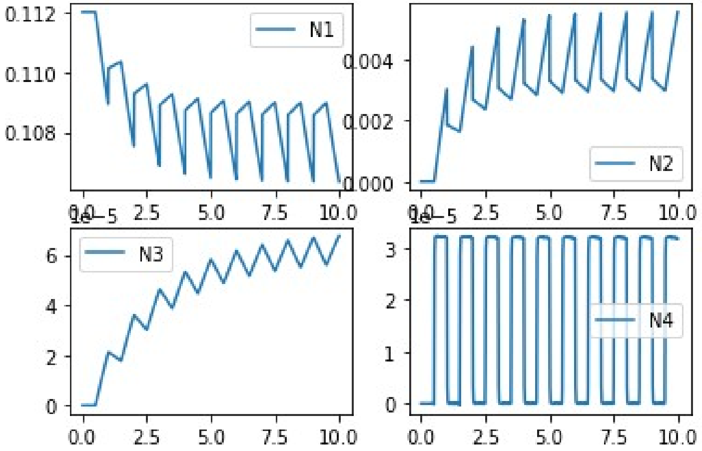


Figure 1. Energy level scheme of Tm^{3+} in Lu_2O_3 (ada

Two timescales involved: pumping/relaxation ~100us-1ms, extraction ~10ns

Extraction retrieved from a "lookup table" with results obtained using optical simuations



- Atomic dynamics simulations confirms MPE acts to reduce optical pump energy needs by a factor 2-3
- Role of CR critical for achieving target extraction over a reasonable # passes
- Effects of pump duty cycle not negligible for overall efficiency

Summary and conclusions

- Conceptual and technical design of a <100fs, >500mJ, 1kHz amplification chain based on Tm:Lu2O3 carried out; extraction efficiency up to ~10% predicted

- Active mirror concept with side pumping designed. General optical numerical model of diode pumping developed; pretty homogeneous pumping distribution can be obtained by a suitable tuning of diode (bar) number, focusing, ...

- Active mirror cooling optimized using fluid/thermal modelling; optimization of fluid pipes/jets design expected to allow heat trasnfer coefficients up to 40000 W/(m2 K) → extraction expected from optical modelling feasible while keeping reasonable ceramic temperatures

- Optical characterization of a first Tm:Lu2O3 ceramic sample from Konoshima carried out
  - Slope efficiency up to ~70%
  - Hint of >1.5x inversion population enhancement due to cross-relaxation

- Numerical modelling of atomic transition dynamics ongoing; dynamics of multi-pulse extraction observed (at 1kHz rep rate), in agreement with simulations